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HEMODYNAMICS OF THE CORONARY CIRCULATION DURING CARDIAC ARRHYTHMIAS*

Anginal pain, electrocardiographic abnormalities and morphological changes indicative of myocardial ischemia often result from fast cardiac arrhythmias. During a tachycardia, a state of relative coronary insufficiency may occur because of the increased nutritional demands of the myocardium resulting from the increased work of the heart, even though the coronary arteries are normal. Myocardial ischemia associated with arrhythmias also may be due to one or more of the following factors which reduce the coronary flow: (1) a drop in systemic blood pressure, and hence coronary perfusion pressure; (2) decreased cardiac output due to inadequate cardiac filling during the shortened diastole or weak ventricular contraction; (3) increased coronary arteriolar resistance.

Previous investigators[1, 2] have measured the coronary flow with the rotameter before and after the induction of auricular fibrillation and tachycardia and ventricular tachycardia by electrical means. These studies indicate that the coronary flow diminishes for a few seconds following the onset of a rapid arrhythmia, and then returns toward or above its control value.

Because these conclusions do not agree with the clinical facts and because the techniques and interpretations are open to question, we reinvestigated the problem, using additional techniques.[3-7] The coronary flow was measured in 226 dogs and 4 pigs by: (1) the open-drop method; (2) the rotameter; and (3) the photoelectric dropmeter. Coronary artery and sinus flows, coronary blood pressure, cardiac output, central venous pressure and systemic blood pressure were measured simultaneously in various arrhythmias in dogs and pigs anesthetized by pentobarbital or chloralose. These arrhythmias included premature auricular and ventricular systoles, auricular tachycardia, flutter, fibrillation and ventricular tachycardia and fibrillation produced by mechanically stroking the heart or by the application of aconitine. Spontaneously occurring arrhythmias were also studied.

The technique of measuring the coronary blood flow has been fully described elsewhere.[3-5] Essentially, it consists of severing a coronary artery and then cannulating the proximal and distal cut ends. The continuity of the coronary flow is then re-established by connecting the ends of the two cannulae together so that the coronary blood passes through a flowmeter (either a rotameter or a photoelectric dropmeter). With either of these two flowmeters, the coronary flow is measured with the peripheral coronary resistance intact. The total coronary sinus flow was often measured simultaneously with the coronary artery flow.

The coronary flow is also measured by the open-drop method.[3] This consists of allowing the blood from the open cannulae to drop freely into graduated test tubes. The measurements from the proximal coronary cannula give the antegrade or forward free flow; the measurements from the distal cannula give the retrograde free flow. This retrograde blood is derived from the anastomotic collateral vessels. By comparing the simultaneous retrograde (collateral) and the antegrade (forward) free flows, an estimate of the adequacy of the collateral circulation is made.[3] It is obvious that the results obtained by this method are affected by the absence of peripheral coronary arteriolar resistance. However, it is the only method by which the retrograde flow can be compared to the simultaneous antegrade flow under the same physical conditions.

RESULTS

Premature Auricular Systoles and Premature Ventricular Systoles

When the coronary artery or sinus flow was measured with the photoelectric dropmeter, pre-

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mature auricular systoles and premature ventricular systoles were found to cause an average decrease in the coronary flow of 5 and 12 per cent, respectively, of the control value. Premature ventricular systoles reduced the coronary flow more than premature auricular systoles. In some animals, when the premature ventricular beats were very frequent (as, for example, during bigeminy) the reduction in coronary flow was about 25 per cent. In 86 dogs, a reduction of both the antegrade and retrograde coronary flows was found to occur in 70 instances. During extrasystoles, the coronary blood pressure and the simultaneously measured systemic blood pressure dropped considerably in both systole and diastole. There appeared to be little ejection of blood from the ventricle during many of the premature systoles. This drop in cardiac output and blood pressure is caused by inadequate filling of the heart during the shortened diastole and probably accounts for the decrease in coronary flow during a premature systole.

Paroxysmal Auricular Tachycardia

With an increase in ventricular rate up to 160 or 180 per minute, the cardiac output and coronary artery and sinus flow increased. With the onset of more rapid auricular tachycardia (above 180-200 per minute), the systemic and coronary blood pressures usually decreased. In many instances, the blood pressure fell to shock levels and then the cardiac output dropped as much as 67 per cent. The faster the ventricular rate, the greater was the drop in the aortic and coronary blood pressures, cardiac output and also the coronary artery flow. With slowing of the ventricular rate, the coronary artery flows and coronary and systemic arterial blood pressures returned to or above normal.

During rapid tachycardias, the average reduction in the coronary artery flow by the rotameter and dropmeter methods was 38.2 and 35.7 per cent, respectively. The range was from 12 per cent to 65 per cent. The open-drop method revealed similar parallel drops in both the antegrade and collateral coronary artery circulations. When the rhythm was converted to normal, the flows usually returned to control values within a few minutes. On termination of the tachycardia, sudden elevations in systemic blood pressure often occurred, due to increased total peripheral resistance as described by Wégria.[1, 2] These elevations resulted in a transient rise in coronary artery flow, lasting a few seconds.

In marked contrast, the coronary sinus flow did not always parallel the depressions which occurred in the coronary artery flow. It was observed that the coronary artery flow often dropped 20 per cent, while the coronary sinus flow remained almost the same. When the blood pressure dropped to shock levels, the coronary sinus flow also was diminished. If the ventricular rate slowed slightly so that the blood pressure suddenly returned to normal from shock levels, supernormal coronary sinus flow of oxygenated blood resulted, lasting up to 20 seconds.

Simultaneously recorded coronary artery flows did not rise to nearly the same degree with the transient return of blood pressure levels. This suggests that a shunting mechanism must take place, increasing the blood supply to the myocardium during periods of ischemic hypotension to compensate for the decreased coronary artery flow. This increases the blood flow of the myocardium for short periods of time as much as threefold. This might be similar to the "spontaneous change" in coronary flow described by Katz, et al.[8] For practical purposes, our observations indicate that the coronary sinus flow drops markedly when the ventricular rate exceeds around 190 per minute, or whenever marked hypotension exists, even at slower rates.

It is difficult to attribute the drop in coronary flow to any one physiological factor. However, the drop in aortic blood pressure is probably a principal determinant, because when the aortic blood pressure is restored, either by an aortic snare or pressor drug, the coronary flow again returns towards normal. The peripheral coronary artery resistance, which usually increases during a tachycardia because of a shortened diastole and relatively longer systole, must be an additional factor affecting the coronary flow. Because of its coronary dilator action and pressor effect, noradrenalin has a beneficial effect in the treatment of tachycardias when hypotension exists.[5]

Auricular Fibrillation

When auricular fibrillation with rapid ventricular rates occurred, the blood pressure in the systemic circulation and in both the proximal and distal segments of the cannulated coronary artery invariably fell, regardless of the mode of production of the arrhythmia. Using the open-drop method, both segments of the coronary flow were found to be similarly affected. The average reduction in antegrade (forward) free coronary flow was found to be 32.9 per cent, and in the retrograde (collateral) free flow was 39.8 per cent. With the rotameter and dropmeter, an even greater impairment in coronary flow was found: 40.3 and 44.4 per cent, respectively. The faster the ventricular rate, above 180 per minute, and the more irregular the rhythm, the lower was the blood pressure, cardiac output and coronary flow. This reduction was probably due to inadequate filling of the heart with the shortened diastole because it was accompanied by a rise in central venous pressure. Again, as the ventricular rate slowed, the blood pressures and the coronary blood flow returned toward normal. In some experiments, when auricular fibrillation persisted for many hours, the coronary flows re-

mained at the much reduced values. However, when the rhythm was converted to regular sinus rhythm, the systemic and coronary pressures and coronary blood flow again returned to the control values. The peripheral coronary resistance could not be accurately assessed because of fluctuations of coronary blood pressure during the paroxysm of fibrillation.

Coronary sinus flow showed rapid fluctuations with the rapid changes in systemic blood pressure, so typical of auricular fibrillation. The coronary sinus flow was often reduced as much as 30 per cent, only to rise threefold for a few seconds subsequent to a sudden transient rise in blood pressure. When hypotension occurred, the sinus flow remained diminished but usually was less impaired than the simultaneously recorded coronary artery flow.

Auricular Flutter

The coronary flow and blood pressure and systemic blood pressure did not drop as markedly in auricular flutter as they did in the other atrial arrhythmias, probably because the ventricular rates were slower. The average drop in antegrade free flow was 22 per cent, and in collateral free flow, 18 per cent. The rotameter and dropmeter revealed comparable results. Blood pressures and coronary flows were higher during flutter with 3:1 and 2:1 A-V block than they were during 1:1 flutter, probably because of the slower ventricular rate. Often, when the ventricular rate in flutter was regular and relatively slow, the coronary blood flow remained practically normal. Coronary sinus flow did not diminish in auricular flutter except at very rapid rates or if hypotension occurred. It is of interest that the mortality rate is higher in patients with myocardial infarction if auricular tachycardia or fibrillation supervenes than if auricular flutter occurs. This clinical observation is probably related to the better average coronary flow rate in flutter than in the other two arrhythmias.

Ventricular Tachycardia

When ventricular tachycardia occurred spontaneously after stroking the heart, or by the application of aconitine, the systemic and coronary blood pressure and coronary blood flows dropped precipitously. Both segments of the coronary circulation were similarly affected. The average antegrade free flow was reduced by 52.5 per cent; the retrograde free flow, 58.9 per cent. The range was from 14 to 90 per cent. The rotameter and dropmeter showed a similar diminution in coronary artery flow. The coronary sinus flow was usually diminished, but not always to the same degree as the coronary artery flow. The ventricular rate did not seem to be the only factor in determining the coronary flow.[4, 6] The ventricular rate was often the same as that of the control sinus rhythm; nevertheless, there was a marked depression in the coronary flow. When the ectopic foci were situated at the base of the ventricle, the greatest depression of the coronary flow and blood pressure occurred.[6] The significance of this finding will be discussed later.

Ventricular Fibrillation

With the onset of ventricular fibrillation, the systemic blood pressure and the antegrade and retrograde coronary pressures and flow fell almost to zero.[4]

DISCUSSION AND CLINICAL APPLICATIONS

We have demonstrated that absolute coronary insufficiency occurs in the experimental animal during supraventricular and ventricular tachycardias.[4, 6, 7] We have also shown that the coronary flow and systemic blood pressure is maximal in sinus tachycardia when the sinus rate is around 166 per minute.[7] With faster sinus rates, the coronary flow and blood pressure diminished, and above 190 per minute there was usually a precipitous drop in both the coronary flow and systemic blood pressure. In the patient with a sinus rate of 166 per minute, the nutritional demands of the myocardium may have so increased that the coronary blood supply, although maximal, may be insufficient. Therefore, myocardial ischemia due to a relative coronary insufficiency may occur. With sinus rates above 190 per minute, the coronary flow diminishes precipitously and causes an absolute coronary insufficiency.

It is obvious that the absolute decrease in coronary flow associated with cardiac arrhythmias presents a real danger, even in the absence of coronary arteriosclerosis. If persistent, the inadequate coronary flow can result in irreversible myocardial damage. It would seem clear that this danger is multiplied when significant degrees of coronary narrowing are present. Under such conditions, the coronary flow may be barely adequate during regular sinus rhythm. A small decrement in coronary pressure and coronary flow caused by an arrhythmia may then result in myocardial ischemia which, if persistent, may lead to myocardial infarction or fibrosis.[5]

Katz[9], and others, have described anginal pain during episodes of premature auricular and ventricular systoles. It is known that ischemia of the myocardium may provoke the extra beats and, in a single case, it is difficult to say if the ischemia has caused the premature beats or the premature beats have caused the ischemia. However, we have noted, in specific patients, that the chest pain is often promptly relieved when the extrasystoles are abolished by quinidine or Pronestyl. This suggests that the myocardial ischemia was in-

duced by the premature beats. We and others have observed transient T-wave abnormalities suggestive of myocardial ischemia occurring immediately after premature systoles.[4, 9, 10] This electrocardiographic abnormality occurs particularly in the presence of coronary artery narrowing. There appears to be no satisfactory explanation for its occurrence other than coronary insufficiency induced by the premature systoles. Because there is no compensatory pause following premature auricular systoles, the ventricular rate may be speeded up slightly and this rhythm, therefore, has a less deleterious effect than premature ventricular systoles.

Most textbooks state that premature systoles need not be treated in patients with coronary artery disease. However, in view of the decrease in coronary flow which accompanies frequent premature beats, we agree with Katz and Pick[9] that the elimination of premature systoles can become an important desideratum. This can best be done by the administration of quinidine or Pronestyl. We have corrected multifocal premature systoles instantly in hypotensive patients with a myocardial infarction by the administration of noradrenalin, probably because of the increase in coronary flow.

The hemodynamic behavior of the collateral coronary circulation during arrhythmias is very similar to that of the antegrade (forward) circulation. The collateral coronary flow and blood pressure both decrease during premature systoles and rapid tachycardias. Collateral coronary circulation is not usually well developed in the normal human or canine heart. Significant collaterals are found in only 10 to 15 per cent of subjects.[3] Although considerable development of collateral circulation often occurs after coronary occlusion, it is probable that the functional capabilities of the collateral circulation must be somewhat limited before an occlusion. Following a coronary occlusion, it has been shown that increasing the coronary collateral flow by even a few drops per minute may prevent or limit the extent of an infarct. Therefore, after a coronary occlusion, maintenance of maximum coronary collateral flow is mandatory. Hence, prompt treatment of arrhythmias is urgently indicated, since coronary flow, both antegrade and collateral, is so often significantly decreased by abnormal rhythms. It is imperative, therefore, to treat arrhythmias as promptly as possible in patients with known coronary artery narrowing or occlusion.

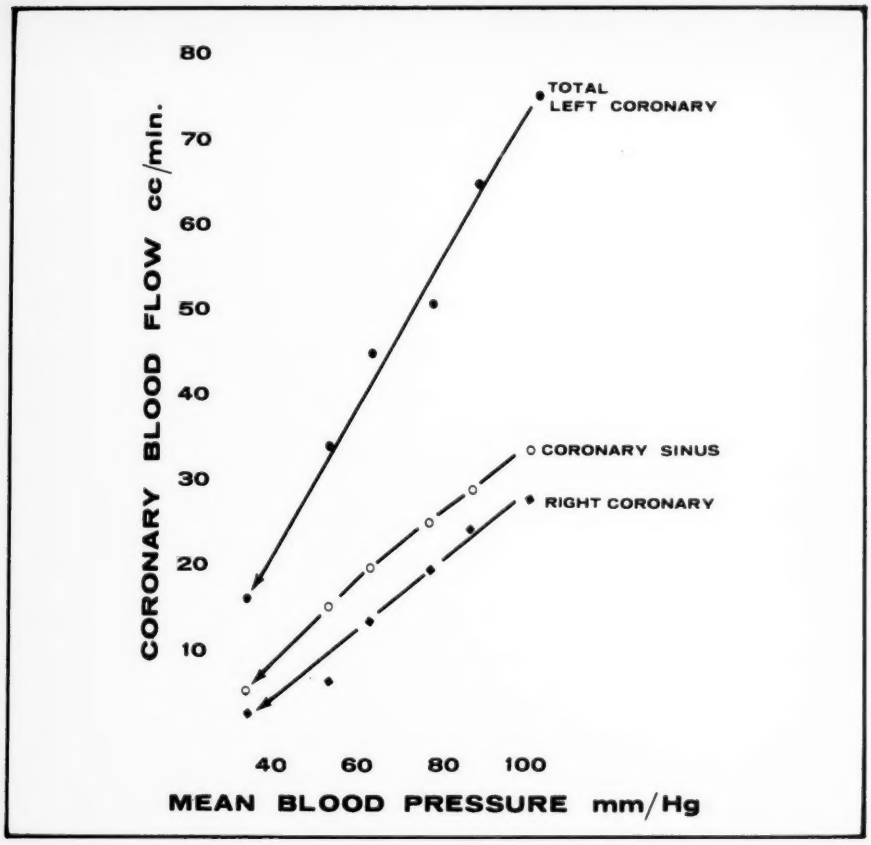
We have described relative differences in the coronary artery and sinus flows recorded simultaneously by a similar instrument. The coronary sinus flow represents a portion of the venous blood returning after it nourishes the myocardium. It usually is less diminished during tachycardias than the coronary artery flow and it often demonstrates temporary supernormal flows on sudden elevation of blood pressure or return to regular rhythm, which are not noted in the arterial circulation. This suggests that there are compensatory shunts in the myocardium which minimize the depression in coronary artery flow caused by the tachycardia.

The total coronary flow may be measured by collecting the coronary flow returning to the right heart.[9] This technique requires the use of an extracorporeal circulation which changes natural peripheral responses, such as systemic blood pressure, cardiac output, peripheral resistance and venous return to the heart and central venous pressure. These extracardiac variables indirectly determine the coronary flow. Much information is obtained by these techniques regarding specific variables, but they create artificial conditions which eliminate the principal factors determining the coronary flow in the intact heart during an arrhythmia. Their results, therefore, may not simulate the clinical event.

We have shown that the coronary flow is a function of the system blood pressure (cf. Page 497) and that the aortic perfusion pressure is probably a principal determinant of coronary flow.[5] Therefore, when an arrhythmia develops in a patient with severe coronary artery disease, there is an urgent need to maintain aortic blood pressure by the use of vasopressor drugs, at least until antiarrhythmic medication takes effect. In the experimental animal, increasing the systemic blood pressure with the aortic snare or vasopressors raises the coronary perfusion pressure and flow, even though the auricular or ventricular tachycardia is still present.

Brachial pressure tracings obtained in the experimental animal during the arrhythmias resemble those in the human and it seems likely that the conclusions drawn from the animal experiments can be applied to man.[11]

In the human and the experimental animal, auricular and ventricular tachycardias may often be terminated by the use of vasopressor agents.[4, 11] It has been suggested that this effect is due to the increased blood pressure stimulating the vagal inhibitory receptors in the arch of the aorta and carotid sinus. It has been observed, however, that arrhythmias can also be terminated with vasopressors in well atropinized patients. This has caused us to search for other mechanisms. We have been able to terminate the auricular and ventricular tachycardias equally well by the application of the aortic snare and vasopressor drugs, thus proving that the rise in blood pressure *per se* inhibits the arrhythmias.[4] Furthermore, the arrhythmias could be terminated by raising the blood pressure after both vagus nerves were severed. Even when the heart was completely denervated, the rapid ectopic arrhythmias could often be corrected by the use of vasopressor drugs.[4] This suggests that the increased blood pressure acts directly on the myocardium, the conduction system, or on an antiarrhythmic center in the heart to terminate the arrhythmia.



EFFECT ON THE CORONARY CIRCULATION OF LOWERING THE BLOOD PRESSURE IN A DOG

Simultaneous blood flow in coronary arteries and coronary sinus, measured by photoelectric dropmeter in a closed system (coronary arteriolar resistance intact). Coronary flow drops in a linear fashion with fall in systemic blood pressure. Left and right coronary flows are reduced one-third when blood pressure drops from 100 to 82 mm. of Hg.

If the arrhythmia is caused by ischemia of the myocardium, it is probable that vasopressor agents terminate the abnormal rhythm by improving the coronary circulation or, in turn, by washing out irritating metabolites.

We have observed in dogs that if the blood pressure is increased above approximately 180 mm. of Hg systolic, dangerous ventricular arrhythmias may develop.[4] For this reason, it is suggested that when administering pressor drugs, the blood pressure be kept below this level. The optimum blood pressure level is probably best maintained by intravenous norepinephrine, whose pressor effect is evanescent and can be carefully titrated from minute to minute. It is well known that the catecholamines, including norepinephrine and other pressor drugs, can themselves induce cardiac arrhythmias independently of their pressor effects. Fortunately, however, these arrhythmias rarely occur with the low concentrations of these agents which are commonly used to raise the blood pressure.

Clinicians have long noted that the clinical course of different patients with ventricular tachycardia may vary considerably. Some may enter into a shock state with a profound drop in blood pressure and a rapidly fatal outcome, while others may not even be aware of an attack of ventricular tachycardia which may persist for weeks. In a group of animals, when we produced ventricular tachycardia by stimulating near the base of the ventricle, more profound reductions in aortic blood pressure and coronary flow occurred than if we stimulated near the apex.[6] This suggests that the site of the ectopic ventricular focus determines whether the arrhythmia will be "benign" or "malignant." A systolic contraction wave of tachycardia, starting at the base of the ventricle, must first drive the blood towards the apex before it can be ejected into the outflow tract at the base of the ventricle. Also, the outflow tract of the heart may contract before the body of the ventricle and this probably reduces the size of the outflow tract during the ejection

period. These factors result in a highly abnormal and ineffective contraction, with marked reduction in the cardiac output, blood pressure and coronary flow. This malignant type of ventricular tachycardia must be treated as a cardiac emergency. We have been successful in maintaining the systemic blood pressure with noradrenalin in a patient with malignant ventricular tachycardia, following a coronary occlusion, until massive doses of quinidine finally restored sinus rhythm hours later.[11]

Thus, in ventricular tachycardia, the ventricular rate is not the only determinant of coronary flow and systemic and coronary blood pressures. The site of the ectopic ventricular focus is the most important factor determining coronary hemodynamics in ventricular tachycardia at rates below 160 per minute. At faster rates, ventricular tachycardia exerts the same deleterious effects upon the coronary circulation, regardless of the site of the focus.[6]

In irregular rhythms, such as premature auricular and ventricular systoles and auricular fibrillation, the degree of prematurity of the beats has a great influence upon the coronary hemodynamics. In general, a very premature beat allows little time for diastolic filling and therefore ejects only a small amount of blood, inadequate to provide normal coronary pressure and flow.

These studies demonstrate that marked impairment of coronary flow and blood pressure occur during various arrhythmias and provide a physiological reason for their treatment. The probable method of action of vasopressor drugs in "aborting" the arrhythmias has been pointed out. The importance of supporting the systemic blood pressure until an antiarrhythmic agent takes effect has been emphasized. The mortality rate, which is still high when an arrhythmia occurs after a coronary occlusion, may be reduced with the judicious use of vasopressor drugs. If vagal stimulating measures fail to terminate the tachycardia in the presence of hypotension, the pressor drugs should be used next with proper precautions. As their action is prompt, they should be administered before quinidine or digitalis is used, because the latter agents might take considerable time to act. A slight rise of aortic perfusion pressure will result in a great improvement of the coronary flow. With an already ischemic myocardium as, for example, after a coronary occlusion, this might make the difference between an extensive or minimal myocardial infarction, or life and death.

CONCLUSIONS

1. It has been demonstrated that many cardiac arrhythmias have a deleterious effect upon the coronary flow. In the patient with coronary artery disease, many commonly encountered arrhythmias should be treated promptly.

2. Compensatory cardiac and extracardiac mechanisms tend to maintain the coronary circulation during tachycardias. These compensatory mechanisms fail in extremely rapid tachycardias and where hypotension supervenes.

3. In all patients, especially those with coronary disease, who develop an arrhythmia associated with a fall in blood pressure, the use of pressor agents is strongly indicated to terminate the arrhythmia or to maintain coronary flow until antiarrhythmic agents have had time to abolish the arrhythmia.

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